What do Multiple Planet Systems Teach us about Planet Formation?

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Abstract.   For centuries, our knowledge of planetary systems and ideas about planet formation were based on a single example, our solar system. During the last thirteen years, the discovery of $\simeq 170$ planetary systems has ushered in a new era for astronomy. I review the surprising properties of extrasolar planetary systems and discuss how they are reshaping theories of planet formation. I focus on how multiple planet systems constrain the mechanisms proposed to explain the large eccentricities typical of extrasolar planets. I suggest that strong planet-planet scattering is common and most planetary systems underwent a phase of large eccentricities. I propose that a planetary system's final eccentricities may be strongly influenced by how much mass remains in a planetesimal disk after the last strong planet-planet scattering event.

1.   Introduction

For centuries, theories of planet formation had been designed to explain our own Solar Systems, but the first few discoveries of extrasolar planetary systems were wildly different than our own. These discoveries led to the realization that planet formation theory must be generalized to explain a much wider range of planetary systems. For example, traditional theories predicted that giant planets would form at several AU and beyond, where temperatures are cold enough for ices to initiate the growth of grains and planetesimals (Lissauer 1993, 1995). Now, we know of over 70 giant planets inside 1 AU and 40 inside 0.1AU (http://www.obspm.fr/planets). Theorists have proposed numerous possible mechanisms to explain the existence of these planets. Typically, they assume that the giant planet formed beyond a few AU, but then migrated inwards through a protoplanetary or planetesimal disk to their currently observed locations (e.g., Goldreich & Tremaine 1980; Lin et al. 1996; Ward 1997; Murray et al. 1998; Cionco & Brunini 2002) and stop before being accreted on the star (e.g., Trilling et al. 1998; Ford & Rasio 2006). Similarly, it had long been assumed that planets formed in circular orbits due to strong eccentricity damping in the protoplanetary disk and remained on nearly circular orbits (i.e., eccentricity ≤0.1; Lissauer 1993, 1995). However, over half of the extrasolar planets beyond 0.1AU have eccentricities ≥0.3, and one is as large as ≃0.95. Theorists have suggested numerous mechanisms to excite the orbital eccentricity of giant planets (e.g., Rasio & Ford 1996; Weidenschilling & Marzari 1996; Lin & Ida 1997; Holman et al. 1997; Murray et al. 1998; Ford, Havlickova & Rasio 2000; Kley 2000, 2004; Chiang & Murray 2002; Lee & Peale 2002; Marzari & Weidenschilling 2002; Ford, Rasio & Yu 2003; Adams & Laughlin 2003; Veras & Armitage 2004; Namouni 2005). In recent years, improved observations of a few multiple planet systems have allowed theorists to determine their current orbital configuration and use that to place strong constraints on the formation of a few planetary systems (Lee & Peale 2002; Ford, Lystad & Rasio 2005).

We review some of the mechanisms proposed to explain orbital migration in disks in §2 and eccentricity excitation in §3. In §4, we review the current knowledge of three particularly well-studied multiple planet systems. We conclude with a discussion of the implications of these multiple planet systems for theories of orbital migration in §5.

2. Orbital Migration

2.1. Interactions with Gaseous Disk

Well before the discovery of extrasolar planets, analytic studies of a planet in a gaseous protoplanetary disk indicated that torques could lead to rapid orbital evolution (Goldreich & Tremaine 1979, 1980). Initially, it was not clear if the net torque would lead to inward or outward migration, but subsequent investigations indicated that the net torque typically leads to an inward migration for a single planet in a quiet disk (Ward 1997). Recently, numerous researchers have conducted detailed hydrodynamic models to better understand the details of the torques occurring at various locations in the disk. While early work focused on torques exerted at Linblad resonances, it is now clear that one must also consider torques occurring at corotation resonances and accretion onto the planet, even once the planet has cleared a gap in the disk (Artymowics & Lubow 1996; Bate et al. 2003; D'Angelo et al. 2003). Unfortunately, these complications demand that simulations include physics spanning a large range of physical scales, and this remains a computational challenge. While multiple groups have found qualitatively similar results, the details remain a matter of active research (e.g., Bryden et al. 1999, Kley 1999). Further complicating matters, recent work has suggested that turbulent fluctuations in the disk may be critical for understanding migration (Rice & Armitage 2003, Laughlin et al 2004).

Shortly after the discovery of giant planets in very short orbital periods, it was realized that the planets likely formed at several AU, but migrated to their current small orbital periods. Torques from a gaseous disk are widely believed to be responsible, as the torques appear more than adequate to cause such large scale migrations. Indeed, the main challenge to such theories is to explain why the migration process is halted before the planet is accreted onto the star. Naively, one would expect the rate of migration to increase with decreasing orbital period and the planets to accrete onto the star. Several halting mechanisms have been proposed (e.g., Trilling 1998), but it is not yet clear to what extent each of these mechanisms is significant. Many migration scenarios require some degree of fine tuning (e.g., disk mass or lifetime) in order to halt the migration at orbital periods of only 1.5-4d.

2.2. Interactions with a Planetesimal Disk

A disk of small solid bodies (e.g., protoplanets, planetesimals, pebbles) can remain long after the gaseous protoplanetary nebula disperses (Goldreich, Lithwick, Sari 2004). If this disk is sufficiently massive, then a giant planet could migrate through the disk by scattering planetesimals (Murray et al. 1998; Cionco & Brunini 2002; Del Popolo & Eks 2002). Migration all the way to a few stellar radii requires that the mass of planetesimal in the disk be large compared to the observed disk masses of protoplanetary disks in Taurus and Ophiuchus (Beckwith & Sarget 1996). Still, typical disk masses are expected to result in a smaller amount of migration. For a single giant planet, the planetesimals that can be scattered at a given time come from a relatively small range of semi-major axes near mean-motion resonances, and the density of planetesimals must exceed a significant threshold to power an extended period of migration. When there is more than one planet, the dynamics can become significantly more complex and the feeding zones significantly enlarged. For example, in our own solar system, Saturn, Uranus, and Neptune are inefficient at ejecting planetesimals, but efficiently scatter them inwards, enabling Jupiter to eject them from the Solar System (Fernandez & Ip 1984, Malhotra 1995).

3. Eccentricity Excitation

3.1. Mutual Planetary Perturbations

Mutual gravitation perturbations in multiple planet systems can lead to significant orbital evolution.

Secular Planetary Perturbations Secular perturbation theory approximates each planet as a ring of mass smeared out over the planet's orbit. In the secular approximation, the semi-major axes remain constant, but the eccentricities, inclinations, and orientations of the orbits evolve with time (Murray & Dermott 1999). If the orbital planes are highly inclined ($\geq 40°$), then even a system with initially circular orbits can undergo large eccentricity oscillations (the "Kozai effect"; Kozai 1962; Holman et al. 1997; Ford, Kozinsky & Rasio 2000). While this effect is almost certainly important for some planets orbiting stars that have a wide stellar binary companion, dissipation in the protoplanetary disk makes it very unlikely for giant planets to form with large relative inclinations (Lissauer 1993). In the low-inclinations and low-eccentricity regime, the eccentricity and inclination oscillations decouple to lowest order, and angular momentum is exchanged between the various planets on long timescales (Murray & Dermot 1999). The low-inclination, high-eccentricity regime can be studied by the octupole approximation (Ford, Kozinsky, Rasio 2000; Lee & Peale 2003) or by a numerical averaging procedure (Michtechenko & Malhotra 2004). In both approximations, the inclinations remain small, and conservation of angular momentum requires that secular perturbations can only transfer angular momentum from one orbit to another. Therefore, secular planetary perturbations can only excite significant eccentricities, if there is already at least one eccentric planet in the system.

Strong Planet-Planet Scattering If planet formation commonly results in planetary systems with multiple planets, then it should be expected that the initial configurations will not be dynamically stable for time spans orders of magnitude longer than the timescale for planet formation (e.g., Levison, Lissuaer & Duncan 1998). When protoplanetary core form, they do not know how much gas they will eventually accrete, so planets will accrete too much mass to remain stable for the lifetime of their star. Additionally, giant planets must form while there is still significant gas in the protoplanetary disk, so they are likely subject to significant eccentricity damping which prevents eccentricity growth. Once the protoplanetary disk disperses, the eccentricity damping is removed and mutual gravitational perturbations can start exciting eccentricities that will eventually lead to close encounters.

In multiple planet systems which are dynamically unstable, close encounters and strong planet-planet scattering can produce large eccentricities (Rasio & Ford 1996; Weidenschilling & Marzari 1996). For systems of two giant planets initially on nearly circular orbits, dynamical instabilities are typically resolved by two planets colliding and producing a more massive giant planet in another low-eccentricity orbit or by one planet being ejected from the system, leaving behind the other planet in an eccentric orbit. For comparable mass planets, this typically results in large eccentricities (Ford, Havlickova & Rasio 2001), but this same mechanism naturally produces lower eccentricities when the planet mass ratio differs from unity (Ford, Rasio & Yu 2003). While the distribution of eccentricities depends on the planet mass ratio distribution, the two planet scattering model predicts a maximum eccentricity of $\simeq 0.8$, independent of the mass ratio distribution. This compares favorably with the observed distribution of extrasolar planet eccentricities, since only one of the $\simeq 170$ known extrasolar planets has an eccentricity greater than 0.8 (and the exceptional planet is in a known binary). The fraction of systems which result in ejections and eccentric planets depends on the orbital distance and effective radius for collisions (Ford, Havlickova & Rasio 2001), as well as the ratio of planet masses (Ford, Rasio & Yu 2003). While ejections dominate for giant planets at several AU, collisions are more frequent for comparable planets inside ~ 1AU.

Therefore, strong planet-planet scattering can easily produce the large eccentricities of giant planets at large separations, but by itself would predict that low-eccentricity orbits would be more frequent at small separations.

Simulations of planet-planet scattering often begin with closely spaced giant planets (e.g., Rasio & Ford 1996; Ford, Havlickova & Rasio 2001). This is necessary for dynamical instabilities to occur in systems with only two planets initially on circular orbits. While such systems facilitate the systematic study of the relevant physics, real planetary systems likely have more than two massive bodies. In planetary systems with multiple planets, dynamical stabilities are common even for systems with large initial separations (Chambers, Wetherill & Boss 1996; Marzari & Weidenschilling 2002). Additionally, such systems can persist uneventfully for $\sim 10^{6-8}$yr, before chaos leads to close encounters and strong planet-planet scattering.

Dynamical Relaxation If protoplanetary disks form many planets nearly simultaneously, then planet-planet scattering may lead to a phase of dynamical relaxation. Several researchers have numerically investigated the dynamics of planetary systems with 10-100 planets (Lin & Ida 1997; Papaloizou & Terquem 2001, 2002; Adams & Laughlin 2003; Barnes & Quinn 2004). Initially, such systems are highly chaotic and close encounters are common. The close encounters lead to planets colliding (creating more massive planet) and/or planets being ejected from the system, depending on the orbital periods and planet radii. Either process results in the number of planets in the system being reduced and the typical separations between planets increasing. The system gradually evolves from a rapidly unstable state to states which will endure longer before the next collision or ejection. Such systems typically evolve to a state with 1-3 eccentric giant planets which will persist for the lifetime of the star. In systems with at least two remaining planets, the typical ratio of semi-major axes of the innermost planets is typically large, but show considerable variation across different systems, $\langle a_2/a_1 \rangle = 25 \pm 24$ and 11 ± 7.8 for two different mass distributions (Table. 4 of Adams & Laughlin 2003). These distribution of final eccentricities in such systems displays a breadth comparable to the observed distribution of eccentricities of extrasolar planets, but underproduce planets with small eccentricities. Although dynamical relation does not predict a strict upper limit for the eccentricities generated (as does planet-planet scattering with two planets initially on circular orbits), extreme eccentricities are unlikely ($p(e > 0.8) \leq 0.1$; see Fig. 7 of Adams & Laughlin 2003), since the final eccentricities are the result of a succession of ejections and/or collisions.

Since the initial evolution is strongly chaotic, the results of such simulations are relatively insensitive to the exact choice of initial conditions, but bounded by conservations of energy and angular momentum. This partially explains the similar results of several groups using different initial conditions. However, nearly all such simulations have considered purely gravitational forces. In fact, planetary systems may evolve via dynamical relaxation while the disk still has a significant amount of mass in gas or planetesimals. Either a gas or planetesimal disk is likely to provide a significant amount of dissipation which could significantly alter the evolution of the system. While some work has investigated the effects of dissipative gaseous disk which drives convergent migration between two planets and lead to close encounters (Adams & Laughlin 2003; Moorhead & Adams 2005), much more work remains to be done to explore the wide range of parameter space which exists for systems with multiple planets and a dissipative disk.

4. Three Multiple-Planet Systems

First, we review recent research on the history of three well-studied multiple planet systems orbiting three solar type stars: the Sun, GJ 876, and Upsilon Andromedae (υ And). Several other multiple planet systems have been discovered by radial velocity searches, but either the planets interact too weakly to provide dynamical constraints on planet formation or the published observations are not yet sufficient to precisely

constrain their dynamics. Even though high precision measurements are also available for the planets orbiting pulsar PSR 1257+12, we do not include this system, since it's formation may have been very different than planet formation around solar type stars.

4.1. The Solar System

Despite centuries of study and *it situ* measurements by space probes, the formation of giant planets in our solar system remains a matter of significant debate. In particular, it is not certain whether giant planets form via the gradual accretion of a rocky core or via direct gravitational collapse. According to the gravitational instability model, giant planets are formed by gravitational instabilities in the protoplanetary disk, much like binary stars (Boss 1995, 1996). These simulations are very computationally challenging, so they are not able to include all the relevant physics. Whether or not giant planets form depends on the simplifying assumptions used for the simulation. While some numerical simulations form massive giant planets in a few orbital times, these typically start from disks that are violently unstable. Further, these typical integrations are run for such a short period of time that they can not start from plausible initial conditions. Recent simulations have considered disks that start from a stable state and gradually approach instability via cooling (Pickett et al. 2003; Mejia et al. 2005). These simulations form rings and can temporarily fragment, if the cooling time is sufficiently rapid, but they have not resulted in forming stable giant planets. In principle, the main advantage of the gravitational instability model is that it might be able to form giant planets rapidly, even at large orbital separations. Another potential advantage is that the giant planets would typically be formed in eccentric orbits. Thus, the significant eccentricities of extrasolar planets could be explained without invoking any additional mechanisms for eccentricity excitation.

According to the competing model of core accretion, collisions between rocky planetesimals result in the gradual growth of a rocky core (Lissauer 1993). Once the core becomes sufficiently massive, it accretes a large quantity of gas from the protoplanetary disk (Pollack et al. 1996). Several details of this model remain active areas of research (e.g., "Why do collisions between planetesimals result in accretion rather than shattering?" and "How do small planetesimals avoid rapid orbital decay in the protoplanetary disk?"). Still, there is little doubt that core accretion must explain the formation of the terrestrial planets, asteroids, and other small bodies in the solar system. However, there is active debate whether core accretion could have formed the cores of Uranus and Neptune before the gas disk dissipated. This has led some researchers to propose that Uranus and Neptune, and perhaps all four giant planets, may have formed via gravitational instability. Other researchers have proposed refinements to the core accretion model that could allow for the more rapid formation of Uranus and Neptune. Here we summarize two recent attempts to explain the formation of Uranus and Neptune within the core accretion framework.

Two similar scenarios for forming Uranus and Neptune via core accretion both suggest that they initially formed at much smaller orbital distances, where the timescales relevant for planet formation are shorter. In one version, Thommes, Duncan & Levison (1999) proposed that Uranus and Neptune formed much closer to the Sun than their current orbital separations, perhaps even between Jupiter and Saturn. As the disk began to dissipate, planet-planet scattering excited large eccentricities and caused their orbits to extend well beyond Saturn. Then dynamical friction in the protoplanetary disk would have circularized their orbits at orbital separations comparable to those we see today. In a slightly refined version, Uranus and Neptune again would have initially formed closer to the Sun than their current orbital separations (but still beyond Saturn). This closely packed system could survive for an extended period of time if the eccentricities of all four giant planets were significantly smaller than they are today. Planetesimal scattering would have caused Jupiter to migrate slightly inwards, while Saturn, Uranus, and Neptune would have migrated outwards. The eccentricities would have remained small until Saturn crossed the 2:1 mean motion resonance with Jupiter. This divergent

resonant crossing would not result in resonance capture, but would excite significant eccentricities that would propagate throughout the system. Uranus and Neptune would be scattered outwards, but could have circularized near their current orbits due to dynamical friction with a planetesimal disk (Fig. 1; Tsiganis et al. 2005). This scenario is particularly appealing, since n-body simulations show that it can also reproduce several other observed properties of the solar system (Morbidelli et al. 2005; Gomes et al. 2005; Strom et al. 2005).

Another possibility is that a collisional cascade maintained a significant fraction of the disk mass in small rocky bodies, even after protoplanets have formed (Goldreich, Lithwick & Sari 2004). In this scenario, several Uranus and Neptune-mass protoplanets could have formed near the current location of Uranus and Neptune, since dynamical friction damped the random velocities and gravitational focusing allowed them to accrete more rapidly than conventionally assumed in the core accretion model. Eventually, the mass in the small bodies must have decreased to the point where dynamical friction was no longer sufficient to prevent the protoplanets from exciting each other's eccentricities. Then the protoplanets could have close encounters and scatter each other. In the solar system, several massive proto-planets would have been scattered from near Neptune inward to Uranus, then on to Saturn and Jupiter, before being ejected from the Solar System. Once Uranus and Neptune were the only remaining massive bodies remaining, both planets would be expected to have large eccentricities from scattering nearly comparable mass protoplanets inwards (Chambers 2001). Therefore, some mechanism for eccentricity damping would be necessary to explain their current low eccentricity orbits. The circularization could be caused by dynamical friction and planetessimal scattering in what remains of the planetessimal disk.

4.2. GJ 876

Three planets have been discovered around the M4 dwarf, GJ 876 (Marcy et al. 2001; Rivera et al. 2005). The most recently discovered planet (d) has a minimum mass of $\simeq 6 M_{\oplus}$ planet and orbits at 0.02AU, but is not essential for our subsequent discussion of the orbital evolution of the outer two planets. The two more massive planets (b & c) have minimum masses of 1.9 and 0.6 M_{Jup} and orbit at 0.21 and 0.13AU, respectively. The middle planet has an eccentricity $\simeq 0.2$, but the outer planet's eccentricity is much smaller (≤ 0.03). These planets are particularly interesting, since they are near a 2:1 mean motion resonance, and mutual planetary perturbations have already been observed (Laughlin et al. 2005).

Since mean motion resonances occupy only a small fraction of the available phase space, one might naively assume that it is unlikely for two planets to form in a mean motion resonance. However, if significant planetary migration and multiple planet systems are both common, then planets could form away from mean motion resonances and differential migration could cause the planets approach a mean motion resonance. If the migration is both smooth and convergent, then as planets approach mean-motion resonances, they can be efficiently captured into a low-order mean-motion resonance. Thus, the pair of planets in GJ 876 suggests that significant migration is likely to have occurred in that planetary system. If the migration were to continue after resonant capture, then both planets would migrate together, leading to significant eccentricity evolution (Peale 1986). Indeed, hydrodynamic simulations of two planets embedded in a gaseous disk confirm this behavior (Bryden et al. 2000; Kley 2000; Snellgrove, Papaloizou, Masset & Nelson 2001; Papaloizou 2003; Kley et al. 2005) Therefore, eccentricity excitation via resonance capture is a natural explanation for the observed eccentricities for those extrasolar planetary systems which participate in low-order mean-motion resonances. This possibility has been studied intensively in the context of GJ 876 (Lee & Peale 2002; Snellgrove, Papaloizou & Nelson 2001; Kley et al. 2005), as well as extrasolar planetary systems more generally (Lee 2004; Nelson & Papaloizou 2002).

Lee & Peale (2002) studied the evolution of GJ 876b & c, assuming initially well-separated circular orbits and a smooth convergent migration leading to capture in the

2:1 mean motion resonance. This naturally leads to eccentricity excitation and can easily generate the observed eccentricity of planet c and a small eccentricity for planet b. In fact, the eccentricity excitation due to resonance capture is so efficient that this places significant constraints on the migration history. In one scenario, the migration would have led to capture in the 2:1 mean motion resonance, but the migration must have halted very shortly afterwards. Lee & Peale (2002) estimate that the semi-major axis of the outer planet could only decrease by 7% after resonance capture, requiring the protoplanetary nebula to dissipate at nearly the same time as the capture into resonance. Since this scenario would require an unlikely fine-tuning of parameters, they develop an alternative model which includes eccentricity damping due to interactions with the disk of the form $\dot{e}/e = -K\dot{a}/a$, where e is the eccentricity, a is the semimajor axis, the dots represent time derivatives, and K is a numerical constant. Significant eccentricity damping could slow the excitation of eccentricities and allow the planets to migrate by more than 7% after the resonance capture, somewhat reducing the level of fine-tuning needed. If $K \sim 100$, then the eccentricities start to grow after resonance capture, but saturate at near the currently observed eccentricities, eliminating the need for the migration to halt shortly after resonance capture (see Fig. 2, left). More detailed hydrodynamic simulations confirm this finding (Papaloizou 2003; Kley et al. 2004; Kley et al. 2005). Kley et al. 2005 used the revised orbital fits from Laughlin et al. (2004) and found that $K \simeq 40 - 170$ was needed for the eccentricity excitation to saturate near the current values, depending on the inclination of the system (but assuming coplanar orbits with an inclination relative to the plane of the sky greater $35°$, as suggested by radial velocity constraints).

4.3. υ Andromedae

The system of three giant planets orbiting υ And (Butler et al. 1999) also offers clues to the history of orbital migration. Like GJ876, one planet (b) has a short orbital period (4.6d) and is not essential for understanding the dynamics of the outer two planets. The outer two planets (c & d) have orbital periods of 241d and 1301d and eccentricities of 0.26 and 0.28, respectively (Ford, Lystad & Rasio 2005). Soon after their discovery, it was realized that mutual planetary perturbations could cause significant secular evolution of the eccentricities and longitudes of periastron for the outer two planets (Stepinsky, Malhotra & Black 2000; Chiang, Tabachnik & Tremaine 2001; Lissauer & Rivera 2001).

Two models were proposed to explain the eccentricities and longitudes of pericenter for planets c & d. Chiang & Murray (2002) proposed that a protoplanetary disk beyond planet d could *adiabatically* torque planet d. If the longitudes of periastron were initially circulating, then this torque would drive the system towards solutions where the longitudes of periastron librate about an aligned configuration. Once the system was in the librating regime, the torque would damp the libration amplitude. Thus, this model would predict that the the pericenters of the outer two planets would currently be librating with small amplitude about an aligned configuration and that the secular evolution would cause only small variations in the eccentricities. Malhotra (2002) proposed an alternative model in which the outer planet was perturbed *impulsively*, as would be expected if it had a close encounter with another (undetected) planet. In this scenario, the two planets could be either librating or circulating, depending on the relative phases at the time of the impulsive perturbation. If the system were librating, then this model would generally predict that the libration amplitude would be large and that there would be significant eccentricity oscillations.

The best-fit orbital solution to the early observations suggested that the pericenter directions of the outer two planets were very nearly aligned ($\leq 10°$; Butler et al. 1999), favoring the model for adiabatic perturbations from a disk (Chiang & Murray 2002). However, subsequent observations show that the pericenters are less well aligned than previously thought ($\Delta\omega = 37.6° \pm 4.8°$; Ford, Lystad & Rasio 2005), favoring an impulsive perturbation due to planet scattering.

The planetary system around υ And has an even more remarkable property. This system lies very close to the boundary between librating and circulating solutions. As a result, the eccentricity of the middle planet undergoes very large oscillations with e ranging from from 0.34 to very nearly zero (see Fig. 2, right, after 10^4 years). Stepinsky, Malhotra & Black (2000) recognized that this was possible for *some* orbital solutions consistent with the radial velocity observations. Ford, Lystad & Rasio (2005) used a rigorous Bayesian statistical analysis to demonstrate that the eccentricity of the middle planet periodically returns to nearly zero for *all allowed* orbital solutions (see Fig. 2 of Ford, Lystad & Rasio 2005). This provides a strong constraint on the timescale for eccentricity excitation in υ And ($\simeq$ 100yr). For a planet-disk interaction to excite an eccentricity of $\simeq$ 0.3 would require a very massive disk ($\geq 40M_{\rm Jup}$) exerting a very strong torque only to abruptly stop after $\simeq$ 100yr. Thus, this peculiar orbital configuration would be extremely unlikely, unless both planets were initially on circular orbits and the outer planet were perturbed impulsively by strong planet-planet scattering (Malhotra 2002).

5. Implications for Planet Formation

5.1. Orbital Migration

Regardless of how the giant planets formed, the large number of Kuiper belt objects in mean-motion resonances with Neptune provides strong evidence for significant outward migration of Neptune via planetesimal scattering (Hahn & Malhotra 1999). Numerical simulations have shown that the necessary migration is naturally explained via planetesimal scattering for reasonable disk masses. Only Jupiter is efficient at ejecting planetesimals from the Solar System, but together Neptune, Uranus, and Saturn can scatter planetesimals from near Neptune's orbit inwards to Jupiter. Therefore, Jupiter migrated inwards (slightly due to its large mass), while Saturn, Uranus, and Neptune migrated outwards (Fernandez & Ip 1984; Malhotra 1995).

Initially, theoretical difficulties for forming giant planets at orbital separations of $\simeq$ 0.05AU helped rekindle models of planet migration. The detection of pairs of planets in 2:1 mean motion resonances (e.g., GJ 876 b & c) suggests that smooth convergent migration likely occurred in these systems. Additionally, the fact that migration models can simultaneously match the observed eccentricities for both planets b & c provides further evidence for migration in this system.

5.2. Eccentricity Excitation via Orbital Migration

It is natural to ask if the large torques presumed responsible for orbital migration could also be responsible for exciting orbital eccentricities.

Migration in Planetesimal Disk   Analytical arguments suggest that the planetesimals typically provide a source of dynamical friction (Goldreich et al. 2004). Simulations of a single-planet scattering planetesimals in the Opik approximation also show that eccentricities are usually damped (Murray et al. 1998), although eccentricity excitation may be possible for sufficiently massive planets ($\geq$10 $M_{\rm Jup}$). In our own solar system, it is also believed that scattering of planetesimals may have damped the eccentricities of the outer planets after violent events. Finally, direct simulations of our solar system also demonstrate that planetesimal scattering typically damps eccentricities (Hahn & Malhotra 1999; Thommes, Duncan & Levison 1999, 2002; Tsiganis et al. 2005).

Migration in Gaseous Disk   While the dissipative nature of a gaseous disk naturally leads to eccentricity damping (Artymowicz 1993), a few researchers have suggested that excitation may also be possible. Artymowicz (1992) found that a sufficiently massive giant planet ($\geq$10 $M_{\rm Jup}$) can open a wide gap, leading to torques which excite eccentricities. More recently, Goldreich & Sari (2003) have suggested that a gas disk could

excite eccentricities even for less massive planets via a finite amplitude instability. This claim is controversial, as 3-d numerical simulations have not been able to reproduce this behavior (e.g., Papalouizou et al. 2001; Ogilvie & Lubow 2003). Given the large dynamic ranges involved and the complexity of the simulations, one might question the accuracy of current simulations. For example, three dimensional simulations have suggested that the gaps induced by giant planets might not be as well cleared as assumed in many two dimensional disk models (Bate et al. 2003; D'Angelo et al. 2003). We believe that further theoretical and numerical work is needed to better understand planet-disk interactions. In the mean time, we look to the observations for guidance on the question of eccentricity damping or excitation.

Empirical Evidence   In the GJ876 system, the observed eccentricities are not consistent with eccentricity excitation via interactions with the disk. The current observed eccentricities could be readily explained if interactions with a gas disk led to strong eccentricity damping $K = \dot{e}a/e\dot{a} \gg 1$ (Lee & Peale 2002; Kley et al. 2005). This is in sharp contrast to current hydrodynamic simulations of migration that suggest $K \simeq 1$ and theories that predict $K < 0$ (e.g., Goldreich & Sari 2003; Ogilvie & Lubow 2003). While other planetary systems are not yet as well constrained or studied as GJ 876, the moderate eccentricities of other extrasolar planetary systems near the 2:1 mean motion resonance suggest that GJ 876 is not unique.

The υ And system also provides a constraint on eccentricity excitation during migration. If the outer two planets migrated to their current locations (0.8 and 2.5AU), then they must have been in nearly circular orbits at the time of the impulsive perturbation in order for the middle planet's eccentricity to periodically return to nearly zero. While this does not demonstrate a need for rapid eccentricity damping as in GJ 876, this is inconsistent with models which predict significant eccentricity excitation. Since dynamical analyses severely limit the possibility of eccentricity excitation in both the GJ 876 and υ And systems, we conclude that orbital migration does not typically excite eccentricities, at least for a planet-star mass ratio less than $\sim 0.003 - 0.006$ (those of the most massive planet in υ And and GJ 876).

5.3.   Origin of Eccentricities

Empirical constraints that suggest that interactions with a gaseous disk do not typically excite eccentricities (§5.1). For GJ 876 (and other planetary systems near mean motion resonances) continued migration after resonance capture could excite the eccentricities of the outer two planets. However, this mechanism is insufficient for explaining the eccentricities of extrasolar planets in general, since the majority of observed multiple planet systems are not near a low-order mean-motion resonance. The dramatic eccentricity oscillations of υ And c provide an upper limit on the timescale for eccentricity excitation in υ And ($\simeq 100$yr) and strong evidence for planet-planet scattering in this system (Ford, Lystad & Rasio 2005). Planet-planet scattering in either few-planet systems (Ford, Rasio & Yu 2003) or many-planet systems (Adams & Laughlin 2003) could produce an eccentricity distribution quite similar to that observed for extrasolar planets.

A complete theory of planet formation must explain both the eccentric orbits prevalent among extrasolar planets and the nearly circular orbits in the Solar System. Despite significant uncertainties about giant planet formation, all three mechanisms for forming the Solar System's giant planets (see §4.1) agree that the giant planets in the Solar System went through a phase of large eccentricities. If Uranus and Neptune formed closer to the Sun, then close encounters are necessary to scatter them outwards to their current orbital distances. During this phase, their eccentricities can exceed $\simeq 0.5$ (Tsiganis et al. 2005). Alternatively, if Uranus and Neptune were able to form near their current locations due to eccentricity damping from a disk of small bodies, then several other ice giants should have formed contemporaneously in the region between Uranus and Neptune. The scattering necessary to to remove these extra ice giants would have excited sizable eccentricities in Uranus and Neptune (Goldreich, Lithwick & Sari 2004).

Finally, the gravitational instability model predicts that most giant planets form with significant eccentricities. Therefore, it seems most likely that even the giant planets in our Solar System were once eccentric.

Perhaps the question, "What mechanism excites the eccentricity of extrasolar planets?" should be replaced with "What mechanism damps the eccentricities of giant planets?" Unless giant planets form via gravitational instability, interactions with a gas disk are not an option, since the eccentricities would have been excited after the gas was cleared. Both dynamical friction within a planetesimal disk and planetesimal scattering could damp eccentricities in both the Solar System and other planetary systems. Dynamical friction alone would not clear the small bodies, so either accretion or ejection would be required to satisfy observational constraints (Goldreich, Lithwick & Sari 2004). Planetesimal scattering provides a natural mechanism to simultaneously damp eccentricities and remove small bodies from planetary systems.

Perhaps, *the key parameter that determines whether a planetary system will have eccentric or nearly circular orbits is the amount of mass in planetesimals at the time of the last strong planet-planet scattering event.* The chaotic evolution of multiple planet systems naturally provides a large dispersion in the time until dynamical instability results in close encounters (Chambers, Wetherill & Boss 1996; Ford, Havlickova & Rasio 2001; Marzari & Weidenschilling 2002). Unfortunately, this could significantly complicate the interpretation of the observed eccentricity distribution for extrasolar planets. On a positive note, this model might naturally explain both the eccentric orbits of extrasolar planets and the circular orbits in the Solar System. Future numerical investigations will be necessary to test this model further.

References

Adams, F.C., & Laughlin, G. 2003 Icarus 163, 290.
Artymowicz 1992 PASP 104, 769.
Artymowicz 1993 ApJ 419, 116.
Artymowicz, P. Lubow, S.H. 1996 ApJ 476, L77.
Barnes, R. Qunn, T. 2004 ApJ 611, 494.
Bate, M.R., Lubow, S.H., Ogilvie, G.I., Miller, K.A. 2003 MNRAS 341, 213.
Beckwith, S.V.W. & Sargent, A.I. 1996 Nature 383, 189.
Boss, A.P. 1995 Science, 267, 360.
Boss, A.P. 1996 L&PS, 27, 139.
Bryden, G., Chen, X., Lin, D.C.N., et al. 1999 ApJ 514, 334.
Bryden, G., Rózyczka, M., Lin, D.N.C. & Bodenheimer, P. 2000 ApJ, 540, 1091
Butler, R.P., et al. 1999 ApJ, 526, 916.
Chambers, J.E. 2001 Icarus 152, 205.
Chambers, J.E., Wetherill, G.W. & Boss, A.P. 1996 Icarus 119, 261.
Chiang, E.I. 2003 ApJ 584, 465.
Chiang, E.I., Fischer, D., Thommes, E. 2002 ApJ 564, L105.
Chiang, E.I. & Murray, N. 2002 ApJ 576, 473.
Chiang, E.I., Tabachnik, S, Tremaine, S. 2001 AJ 122, 1607.
Cionco, R.G. & Brunini, A. 2002 MNRAS, 334, 77.
D'Angelo, G., Kley, W, Henning, T. 2003 ApJ 586, 540.
Del Popolo, A., Eks, I.,K.Y. 2002 MNRAS 332, 485.
Fernandez, J.A., Ip, W.-J. 1984 Icarus 58, 109.
Ford, E.B., Havlickova, M. & Rasio, F.A. 2001 Icarus 150, 303.
Ford, E.B., Kozinsky, B., Rasio, F.A. 2000 ApJ 535, 385.
Ford, E.B., Lystad, V., Rasio, F.A. 2005 Nature 434, 873.
Ford, E.B. & Rasio, F.A. 2006, submitted to ApJL.

Ford, E.B., Rasio, F.A., Yu, K. 2003 Scientific Frontiers in Research on Extrasolar Planets, eds. D. Deming & S. Seager (ASP Conference Series, 294), 181.
Goldreich, P., Lithwick, Y., Sari, R. 2004 ApJ 614, 497.
Goldreich, P., Sari, R. 2003 ApJ 585, 1024.
Goldreich, P., Tremaine, S. 1979 ApJ 233, 857.
Goldreich, P., Tremaine, S. 1980 ApJ 241, 425.
Gomes, R., Levison, H.F., Tsiganis, K., Morbidelli, A. 2005 Nature 435, 466.
Hahn, J.M., Malhotra, R. 1999 AJ 117, 3041.
Holman, M., Touma, J., Tremaine, S. 1997 Nature 386, 254.
Kley, W. 1999 MNRAS 303, 696.
Kley, W. 2000 MNRAS 313, L47.
Kley, W., Lee, M.H., Murray, N., Peale, S.J. 2005 A&A 437, 727.
Kley, W., Peitz, J. & Bryden, G. 2004 A&A, 414, 735.
Kozai, Y. 1962 AJ 67, 591.
Laughlin, G., Butler, R.P., Fischer, D.A., Marcy, G.W., Vogt, S.S., Wolf, A.S. 2005 ApJ 622,1182.
Laughlin, G., Steinacker, A., Adams, F.C. 2004 ApJ 608, 489.
Lee, M.H. 2004 ApJ 611, 517.
Lee, M.H. & Peale, S.J. 2002 ApJ 567, 596.
Lee, M.H. Peale, S.J. 2003 ApJ 592, 1201.
Levison, H.F., Lissuaer, J.J., Duncan, M.J. 1998 AJ 116, 1998.
Lin, D.N.C., Bodenheimer, P., Richardson, D.C. 1996 Nature 380, 606.
Lin, D.N.C. & Ida, S. 1997 ApJ, 447, 781
Lissauer, J.J. 1993 ARAA, 31, 129
Lissauer, J.J. 1995 Icarus 114, 217.
Lissauer, J.J. & Rivera, E.J. 2001 ApJ 554, 1141.
Malhotra, R. 1995 AJ 110, 420.
Malhotra, R. 2002 ApJ, 575, 33.
Marcy, G., et al. 2001 ApJ, 555, 418.
Marzari, F. & Weidenschilling, S.J. 2002 Icarus 156, 570.
Mejia, A.C., Durisen, R.J., Pickett, M.K., Cai, K. 2005 ApJ 619, 1098.
Michtechenko, R.A., Malhotra, R. 2004 Icarus 168, 237.
Morbidelli, A., Levison, H.F., Tsiganis, K., Gomes, R. 2005 Nature 435, 462.
Murray, C.D. & Dermott, S.F. 1999 Solar System Dynamics (New York: Cambridge University Press)
Murray, N. Hansen, B., Holman, M., Tremaine, S. 1998 Science 279, 69.
Nagasawa, M., Lin, D.N.C., Ida, S. 2003 ApJ 586, 1374.
Namouni, F. 2005 AJ 130, 280.
Nelson, R.P. & Papaloizou, J.C.B. 2002 MNRAS 333, L26.
Ogilvie & Lubow 2003 ApJ 587, 398.
Papaloizou, J.C.B. 2003 CeMDA 87, 53.
Papaloizou, J.C.B. & Terquem, C. 2001 MNRAS 325, 221.
Papaloizou, J.C.B. & Terquem, C. 2002 MNRAS 332, L39.
Papalouizou, J.C.B., Nelson, R.P. & Masset, F. 2001 A&A 366, 263.
Peale, S.J. 1986 in Satellites, ed. J.A. Burns & M.S. Matthews (Tucson: Univ. Arizona Press)
Pickett, B.K., Majia, A.C., Durisen, R.H., Cassen, P.M., Berry, D.K., Link, R.P. 2003 ApJ 590, 1060.
Pollack, J.B., Hubickyj, O., Bodenheimer, P., Lissauer, J.J., Podolak, M. & Greenzweig, Y. 1996 Icarus 124, 62.
Rasio, F.A. & Ford, E.B. 1996 Science 274, 954.
Rice, W.K.M., Armitage, P.J. 2003 ApJ 598, 55.
Rivera, E.J. et al. 2005 ApJ 634, 625.
Snellgrove, M.D., Papaloizou, J.C.B., Nelson, R.P. 2001 A&A 374, 1092.
Stepinsky, T.F., Malhotra, R., & Black, D.C. 2000 ApJ 545, 1004.
Strom, R.G., Malhotra, R., Ito, T., Yoshida, F., Kring, D.A. 2005 Science 572, 1847.
Thommes, E.W., Duncan, M.J., Levison, H.F. 1999 Nature 402, 635.
Thommes, E.W., Duncan, M.J., Levison, H.F. 2002 AJ 123, 2862.
Trilling, D.E., Benz, W., Guillot, T., Lunine, J.I., Hubbard, W.B., Burrows, A. 1998 ApJ 500, 428
Tsiganis, K., Gomes, R., Morbidelli, A., Levison, H.F. 2005 Nature 435, 459.

Veras, D. Armitage, P.J. 2004 Icarus 172, 349.
Ward, W.R. 1997 Icarus 126, 261.
Weidenschillingm S.J. & Marzari, F. 1996 Nature 384, 619.

See `http://www.nature.com/nature/journal/v435/n7041/fig_tab/nature03539_F1.html`.

Figure 1: Orbital evolution of a hypothetical planetary system similar to the Solar System. The lines show the semimajor axis (middle lines), periastron distance (q; lower lines), and apastron distance (Q; upper lines) for each planet. This n-body simulation started with the giant planets closer together than the Solar System giant planets are today. The planets migrated due to scattering planetesimals from a 35 $M_\oplus$ disk extending out to 30 AU. The vertical dotted line marks the epoch where Jupiter and Saturn crossed their 1:2 mean motion resonance. After this point, large eccentricities were excited and the planets underwent close encounters and strong planet-planet scattering. For example, the orbits of planets U and N cross. Continued planetesimal scattering damps the eccentricities to near the present values for the solar system giant planets. The values at the right indicate the maximum eccentricities of each planet over the last 2Myr. Reprinted by permission from Macmillan Publishers Ltd: *Nature* (Tsiganis et al. 2005), copyright 2005.

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Figure 2: Model for the eccentricity evolution of the outer two planets in GJ 876 due to smooth convergent migration. The solid curves show how the eccentricities are excited following capture into the 2:1 mean motion resonance for different assumptions about the rate of eccentricity damping. The horizontal dashed lines show the approximate observed eccentricities for the planets. Unless there was strong eccentricity damping, continued migration after capture into the 2:1 mean motion resonance would rapidly cause the eccentricities to exceed their observed values. In this model, an outer disk is assumed to torque only the outer planet. More sophisticated models give similar results (e.g., Kley et al. 2005). Note that the inner planet is referred to as 1 in the figure and c in the text, and the outer planet is referred to as 2 in the figure and b in the text. Reproduced by the kind permission of the AAS (Lee & Peale 2002).

See `http://www.nature.com/nature/journal/v434/n7035/fig_tab/nature03427_F4.html`.

Figure 3: Dynamical evolution of a hypothetical planetary system similar to υ And. The top panel shows the semimajor axes (middle lines) and peri and apastron distance (lower and upper lines) for planets similar to the middle (C, dashed line) and outer (D, dotted line) planets around υ And, as well as a hypothetical fourth planet (E, solid line). The innermost planet, B, is not shown, as it plays a negligible role. The lower panel shows the eccentricity evolution for the same numerical integration. After a brief period of dynamical instability, planet E is ejected, leaving the other two in a configuration that is very similar to that presently observed for υ And c and d. Note that the timescale to completely eject the outer planet from the system (after $\simeq$9,000 years in this particular simulation) is much longer than the timescale of the initial strong scattering ($\simeq$100 years). After this initial brief phase of strong interaction, the perturbations on the outer planet are too weak to affect significantly the coupled secular evolution of υ And C and D. Thus, the "initial" eccentricity of υ And C for the secular evolution is determined by its value at the end of the strong interaction phase, rather than that at the time of the final ejection. Reprinted by permission from Macmillan Publishers Ltd: *Nature* (Ford, Lystad & Rasio 2005), copyright 2005.